850 nm Single Mode Oxide-VCSELs for 32 Gb/s Error-Free Transmission in OM4 fiber up to 300 m

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***Abstract*—Short-haul optical links based on 850 nm emission wavelength optical transceivers and multimode fibers are widely deployed in large-scale data communication applications. However, the error-free transmission distance of multimode VCSELs over multimode fiber due to modal dispersion is set to 75 m for 25 Gb/s data rate (IEEE 802.3ba). To further extend the transmission distance beyond 75 m, 850 nm single-mode oxide-confined VCSELs are developed with P_{out} > 2.6 mW and SMSR > 32 dB at the operating current bias. The VCSELs successfully deliver 32 Gb/s error-free transmission for up to 500 m in OM4 multimode fiber.**

Keywords—optical interconnects; vertical-cavity surface-emitting laser (VCSEL); bit-error ratio (BER); error-free data transmission over extended distance and temperature

I. Introduction

Short-haul optical links based on 850 nm emission wavelength optical transceivers and multimode fiber (MMF) are most widely deployed in data centers, high performance computing, and Gigabit Ethernet applications because of their high speed and high data transmission energy efficiency. The vertical-cavity surface-emitting lasers (VCSELs) are the predominant type of devices due to their low cost and highly energy-efficient operation. The first low-threshold oxide-confined VCSELs (oxide-VCSELs) with sub-mA threshold current were realized by Deppe in 1994 [1] for multi-Gigabit energy-efficient optical links. The state-of-the-art 57 Gb/s error-free (BER $\leq 10^{-12}$) data transmission of 850 nm oxide-VCSELs at 25 ˚C were demonstrated by Chalmers University (Sweden) and University of Illinois (USA) [2,3]. We also previously reported state-of-the-art 850 nm oxide-VCSELs achieving 25 GHz bandwidth and 50 Gb/s error-free transmissions at elevated temperature up to 85 °C [4]. However, the typical transmission distance for multimode VCSELs over MMF is limited to 75 m for 25 Gb/s (IEEE 802.3ba) primarily due to modal dispersion in the fiber. In order to minimize the effect of modal dispersion and further extend the optical link error-free data transmission distance over MMF, single-mode oxide-VCSELs are of critical interest to be developed [5].

In this work, room temperature high-speed operation of 850 nm single-mode oxide-VCSELs (SM-VCSELs) with a 6 µm diameter oxide-defined aperture and a top mode-selecting filter (MSF) is demonstrated. The device achieves a laser threshold < 0.7 mA, peak output power P_{out} ~ 2.6 mW, and side-mode suppression ratio (SMSR) > 32 dB. The SM-VCSELs successfully deliver 32 Gb/s error-free data transmission at room temperature over up to 300 m in OM4 MMF without any use of pre-emphasis or error-correction techniques.

II. Laser L-I-V and Spectrum

The SM-VCSEL L-I-V characteristics are measured at room temperature (RT), shown in Fig. 1. At RT, the laser reaches a output power of 2.6 mW at a current bias of 8 mA, measured with a calibrated power meter; the differential resistance is around 128 Ω at 8 mA; the maximum slope efficiency in the linear region is 0.48 W/A. The laser threshold is 0.69 mA. The output power does not show roll-off at 8 mA (I/I_{TH} ~ 12).

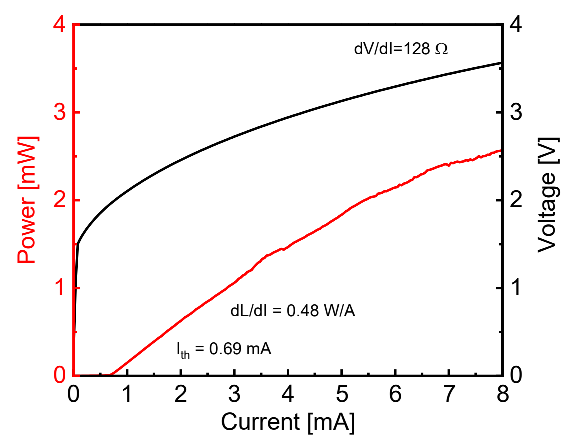

Fig. 1. L-I-V characteristics of an oxide-confined SM-VCSEL operating at RT and 85°C. The laser threshold of 0.69 mA remains almost unchanged due to a detuned cavity design.

Figure 2 illustrates the SM-VCSEL spectra at RT showing the stable single-mode operation with a SMSR > 30 dB consistently from 1 to 8 mA. At the operating current bias of 6 mA, SMSR records at ~33 dB.

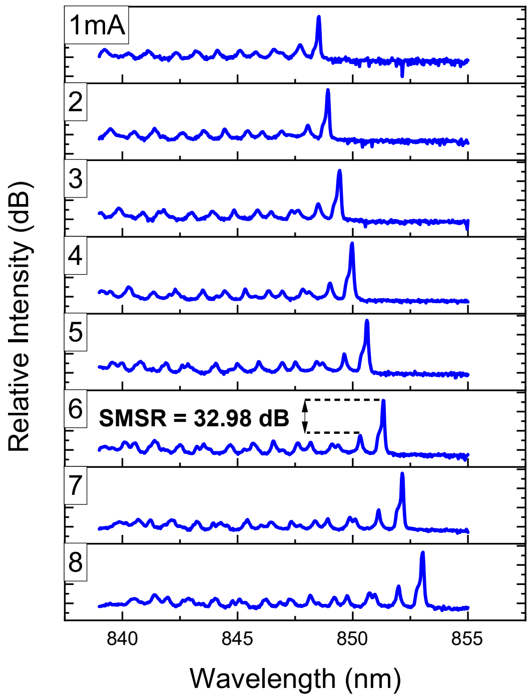

Fig. 2. Bias-dependent SM-VCSEL spectra exhibiting stable single-mode operation from 1 to 8 mA at RT. A SMSR of at least 30 dB is maintained within the operating range.

III. 32 GB/S ERROR-FREE DATA TRANSMISSION UP TO 300 METER

The frequency response of the SM-VCSEL is measured with a 50 GHz PNA Network Analyzer (Agilent E8364B) and a 25 GHz multimode photoreceiver (New Focus 1414-50). The frequency response of the photoreceiver is calibrated and de-embedded from the overall frequency response measurement. Figure 3 shows the SM-VCSEL bias-dependent frequency responses at RT for I/I_{TH} = 2, 4, 6, 8, 10, 12, and 14, where I_{TH} = 0.69 mA. The highest 3dB bandwidth of the SM-VCSEL is recorded at 17.3 GHz at a current bias of 5.5 mA. The laser bandwidth saturates beyond that bias point.

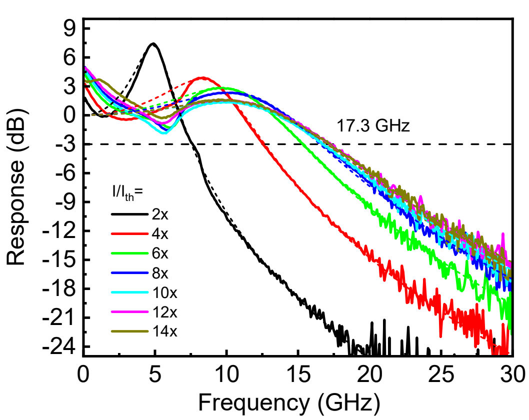

Fig. 3. SM-VCSEL microwave frequency response measurements. A maximum bandwidth of 17.3 GHz is recorded at I = 5.5 mA (I/I_{TH} = 8) at RT.

The SM-VCSEL bit-error-ratio (BER) testing and the corresponding eye diagrams are measured at RT. The data transmission measurement is conducted with a SHF 12103A bit pattern generator, a free-space coupling setup (collimator, reflecting mirrors, and focusing lens), and a 22 GHz photoreceiver (New Focus 1484-A-50). The test bit sequence is a non-return-to-zero on-off keying (NRZ-OOK) 2^7-1 pseudorandom binay sequence (PRBS7). A Keysight DCA-J oscilloscope with a 70 GHz sampling module is used to analyze the eye diagrams. A SHF 11104A error analyzer is used to validate the data transmission. A free-space neutral-density filter is used to adjust the optical power attenuation. A calibrated Thorlabs S120C large-area power sensor is used to measure the total available optical power emitted from the laser before being coupled into fiber. The back-to-back (BTB) power loss due to the measurement setup is calibrated to be about 1.57 dB, which accounts for the finite power loss associated with the collimator, focusing lens, fiber connectors, and FC/APC fiber termination. The received optical power is calculated based on the total available power and the calibrated setup loss.

Figure 4 shows the eye diagram of the SM-VCSEL operating at RT at 32 Gb/s over a distance of 300 m in OM4 fiber with good eye opening and clean transition edges (horizontal scale is 10 ps/div and vertical scale is 20 mV/div).

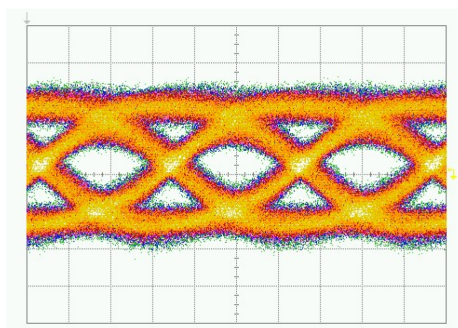

Fig. 4. Eye diagram of the RT operation of SM-VCSEL at 32 Gb/s over 300 m OM4 fiber under error-free (BER < 10^{-12}) transmission condition.

Figure 5 shows the BER as a function of the received optical power at RT, at a data rate of 32 Gb/s over 100 m and 300 m OM4 fiber, and 33 Gb/s over BTB (around 3 m), when the device is biased at 6 mA (I/I_{TH} ~ 8.5, current density ~ 21 kA/cm^2) with a peak-to-peak modulation voltage swing of 1044 mV.

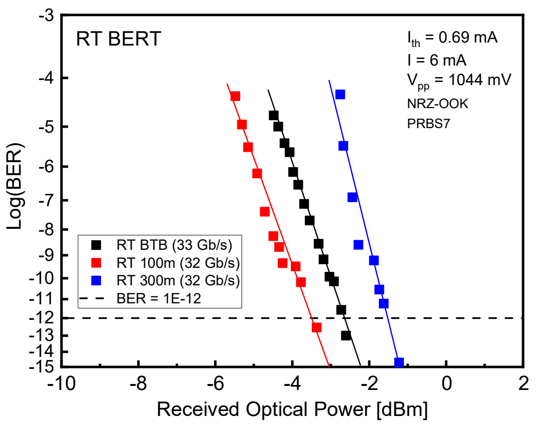

Fig. 5. BER measurement at 33 Gb/s over BTB, and 32 Gb/s up to 300 m over OM4 fiber without pre-emphasis or error-correction. The SM-VCSEL is operated at a current bias of 6 mA and a Vpp of 1044 mV.

For received optical power greater than 0.71 mW (or -1.5 dBm), the SM-VCSEL is able to transmit error-free (BER < 10^{-12} with at least 10 Tb data transmitted) up to a distance of 300 m, and the error rate is limited by fiber dispersion. No pre-emphasis or error-correction techniques are used in the testing.

III. State-of-the-Art Comparison

Figure 6 summarizes the state-of-the-art (SOA) results of 850 nm oxide-confined VCSELs for direct-modulated error-free data transmission at RT over OM4 MMF of various distances reported by Chalmers University of Technology (CUT), Technical University of Berlin (TUB), and University of Illinois (UIUC). The OM4 and OM5 fiber effective modal bandwidth (EMB) limit of 4700 GHz·km at 850 nm wavelength is draw as the solid green line to separate the device-limited operation regime (left-hand side) from the fiber dispersion-limited (right-hand side) regime. For multimode VCSELs, error-free data transmission at 57 Gb/s (BTB) has been reported by CUT (2013) [2] and UIUC (2016) [3, 6], 55 Gb/s (50 m) and 43Gb/s (100 m) by CUT [2], and 50 Gb/s (100 m) by UIUC [7], all of which fall within the device-limited operation regime at given transmission distance.

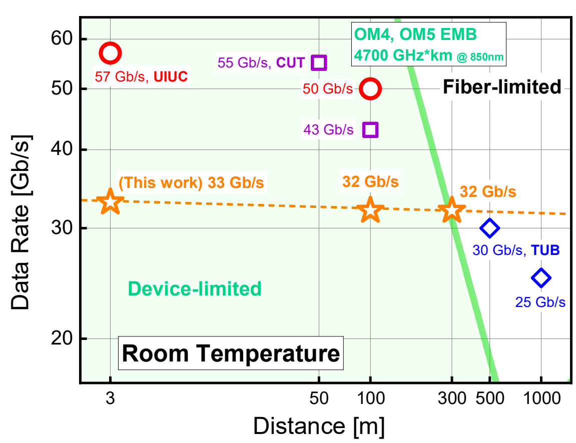

Fig. 6. SOA 850 nm oxide-VCSELs reported results of error-free transmission data rate over distance at room temperature. The data points include Chalmers University (CUT [2]), Technical University of Berlin (TUB [8]), and University of Illinois (UIUC [3,7]).

In this work, SM-VCSELs demonstrate a performance reaching the OM4/5 fiber EMB limit at 32 Gb/s at 300 m, and the data rate penalty to extend from BTB to 300 m is only 1 Gb/s. The results compare well with 30 Gb/s (500 m) and 25 Gb/s (1 km) by TUB [8].

IV. Conclusion

In conclusion, the room temperature stable operation of direct-modulated signal-mode oxide-confined VCSELs are reported; the device demonstrates error-free transmission at a data rate of 32 Gb/s in OM4 multimode fiber up a distance of 300 m, which has reached the dispersion-limited data rate of multimode signal transmission in multimode fiber. This result suggests high speed single-mode VCSELs is key to extending the transmission distance of optical signal over multimode fiber, which can potentially become an economical and energy-efficient upgrade over existing short-haul optical interconnects.

Acknowledgement

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